Title page

Title: Productivity, biodiversity trade-offs, and farm income in an agroforestry versus an arable system

Revision 2

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Abstract

The uptake of diversified farming systems is constrained by a scarcity of evidence regarding financial costs, benefits, and risks. Here, we evaluate the productivity and projected farm income of an agroforestry system, where apples are integrated with arable crops, by combining primary data with ecosystem service and cost-benefit models. Our ecosystem service assessments included: 1) weed and pest associations with arable yields; 2) apple seed set as a proxy for pollination, and; 3) carbon sequestration. Arable yields were up to 11% lower in agroforestry than arable systems, and were significantly negatively associated with weed cover in both systems. Apple yields in agroforestry were similar to typical yields from comparable orchards. Apple seed set was significantly higher in agroforestry than conventional orchards for one of two varieties. Predicted gross mixed income was higher in agroforestry than arable systems in 15 of 18 productivity scenarios over 20 years, which was supported by a case-study. Apple yield and price were the major determinants of gross mixed income. Payments for carbon sequestration were predicted to contribute 47% to 88% of agroforestry establishment costs. This study demonstrates how a diversified farming system can improve farm income, but grant support would reduce the initial negative cash-flow.

Keywords: cost-benefit analysis, diversified farming system, ecological intensification, ecosystem services, Farm-SAFE, silvoarable

1 Introduction

Diversified farming systems have been proposed as a potential means of reducing the environmental harm of agriculture without compromising productivity, through sustainable, or ecological, intensification (Kremen and Miles, 2012; Rosa-Schleich et al., 2019). Despite this, the promotion and adoption of diversified farming systems have seen limited uptake in temperate regions, which is thought to be in part due to a scarcity of evidence regarding the financial costs, benefits and risks relative to conventional non-diversified farming (Kleijn et al., 2019; Rosa-Schleich et al., 2019). Therefore, comparative cost-benefit analyses of these systems at relevant spatial and temporal scales are needed to inform policy and stimulate uptake.

Agroforestry is a diversified farming system which involves the intentional integration of productive trees or shrubs into agricultural land. Relative to monocultures, agroforestry systems can enhance biodiversity and multiple ecosystem functions and services (Smith et al., 2013; Torralba et al., 2016; e.g. Tsonkova et al., 2012; Udawatta et al., 2019). These include marketable services such as natural pest control, pollination, and carbon sequestration (De Stefano and Jacobson, 2018; Pumariño et al., 2015; Staton et al., 2019), but also disservices such as higher abundances of some pest taxa (Staton et al., 2021, 2019). The relative benefits and costs of these services and disservices to productivity and farm income are not clear.

Farmers, landowners and other stakeholders perceive environmental factors such as biodiversity and soil conservation as positive aspects of agroforestry systems in temperate regions, while cashflow and management costs are seen as negative factors (García de Jalón et al., 2018; Valdivia et al., 2012). A lower proportion of farmers in northern Europe compared with the south have a positive perception of the profitability of silvoarable systems (agroforestry in arable settings) (Graves et al., 2008). A survey of farmer perceptions in the UK towards a poplar silvoarable system reported that although most had negative perceptions of its profitability, and there was concern that tree rows could become sources of pests and weeds, 20% would adopt this system if convinced of its higher profitability compared with conventional arable production (Graves et al., 2017). Furthermore, a recent survey of readers of the UK’s Agroforestry Handbook identified a need for financial modelling of agroforestry systems (Raskin, 2020).

Economic modelling of silvoarable systems has a long history (reviewed in Graves et al., 2005). More recently, the Farm-SAFE economic model, primarily intended for timber silvoarable systems, was developed under the Silvoarable Agroforestry for Europe (SAFE) project (Graves et al., 2011, 2007). This model facilitated a series of studies which aimed to evaluate the economic performance of silvoarable relative to arable systems in Europe and Canada. These studies consistently concluded that the farm business profitability of timber silvoarable relative to arable systems was dependent on high value timber trees such as walnut, high timber prices, grant support, or low discount rates (Graves et al., 2007; Palma et al., 2007b; Sereke et al., 2015; Toor et al., 2012; Van Vooren et al., 2016).

Ecosystem service valuations are widely used to demonstrate the added value of environmental benefits of diversified farming systems such as agroforestry. According to recent modelling studies, agroforestry systems can theoretically be more profitable than conventional alternatives after accounting for payments for ecosystem services (or reductions in disservices), including carbon sequestration, reduced greenhouse gas emissions, reduced loss of nutrients and soils, higher groundwater recharge, and reduced pollination deficit (García de Jalón et al., 2017; Giannitsopoulos et al., 2020; Kay et al., 2019).

Nevertheless, cashflow remains a major constraint associated with timber silvoarable systems, because of the time taken for trees to reach harvest, which even for the fastest growing trees is expected to be 20 years (Graves et al., 2007). Furthermore, timber trees might not be eligible for agricultural subsidies and could be subject to legislative requirements for replanting after harvest. These constraints are particularly pertinent to farmers on short-term tenancies, which are especially prevalent in Europe. For example, between 32% and 74% of agricultural land is tenanted in the UK, Germany, and France, with an average tenancy of between 5 and 11.5 years (Ciaian et al., 2012), which is not feasible for timber production.

An alternative form of silvoarable agroforestry is orchard intercropping, where fruit trees such as apple are integrated into arable or pasture (Bhardwaj et al., 2017). Although these systems have historic origins, they have been gaining renewed attention recently as an alternative to timber silvoarable systems, because of their potential to deliver a more rapid return on investment (Gao et al., 2013; Newman et al., 2018; Smith et al., 2016). One innovative example of this system comprises intercropping arable crops with apple trees on appropriate rootstocks (e.g. MM106) to limit their height and subsequent shading impacts on the arable crop, while being reasonably competitive with surrounding ground vegetation. Late-fruiting varieties are selected so that the apple and arable harvests are temporally separated. Typically, single rows of apple trees are intercropped with arable alleys, which are in most cases 24 m wide to facilitate access by modern farm machinery. There has been increasing uptake of this agroforestry system in recent years, particularly in the UK (Newman et al., 2018), despite any studies of its financial performance.

In this study, we aimed to evaluate the productivity, gross mixed income, and contribution of marketable ecosystem services and disservices in this apple-arable agroforestry system, relative to conventional arable systems that consist of a yearly rotation of crops in monoculture. We selected three ecosystem services / disservices based on the availability of empirical data and/or existing models, comprising (i) arable pest and weed pressure, which has been identified as a potential cost of agroforestry by UK arable farmers (Graves et al., 2017); (ii) pollination, which is important for the quality and quantity of apples produced, for example in the absence of pollination, apple yield is reduced by around 55 to 60 % (Garratt et al., 2014; Webber et al., 2020); (iii) carbon sequestration and reduced emissions. We combined primary data collection with a series of ecosystem service and cost-benefit analysis models to explore the following research questions:

1. Does arable crop yield differ between the agroforestry system and arable controls, and is this associated with invertebrate pest abundance and weed cover?
2. How does apple yield in the agroforestry system compare to typical orchard yields, and does apple pollination differ between agroforestry and orchard systems?
3. What is the value of carbon sequestration and reduced emissions in the agroforestry system compared with the arable controls?
4. Theoretically, how does gross mixed income of the agroforestry system compare with arable controls, how does empirical case-study data compare to these theoretical expectations (cost-effectiveness analyses), and which factors most strongly influence gross mixed income (sensitivity analysis)?

2 Methods

2.1 Arable yields and associations with pests and weeds (Question 1)

To compare crop yields between the agroforestry and arable systems, we sampled cereal yield (scaled up to tonnes per hectare) from three UK sites (see Supplementary Material 1). Each site was a working farm containing (i) an agroforestry field, configured in an alley-cropping arrangement where single tree rows were intercropped with 24 m wide arable crop alleys, and (ii) an arable field under the same management. Two years (i.e. two harvests) of data were collected for each site, between 2018 and 2020. The sampled cereal crops comprised winter oats (2 sites), winter wheat (2 sites) and spring barley (1 site). At each site, samples were collected from 12 points in the agroforestry field, located 0.5, 5 and 9.5 m from the tree row, and from 16 points within the arable field following the same pattern around ‘virtual’ tree rows with additional samples at 0 m. Each grain sample was taken from a 50 x 50 cm quadrat, within one week of the field harvest commencing. Samples were threshed using a Wintersteiger Hege 16 and then weighed. Models were built to test the effect of farming system (agroforestry versus arable), crop type and distance from tree row on yield (Table 1).

Table 1. Variables and data subsets used to build linear models, mixed models, and generalised linear mixed models. ‘Farming system’ refers to agroforestry versus arable/orchard. Analysis was undertaken in R version 3.5.2 (R Core Team, 2018) using the ‘lme4’ package (Bates et al., 2015). OLRE = observation-level random effect, to account for overdispersion.

Response	**Fixed effects**	**Random effects**	**Subset**	**Family**
Grain weight	Interaction between farming system, and crop type (barley/wheat or oats), with main effect for farming system removed	Site, year	-	Gaussian
Grain weight	Distance from tree row	Site, year	Agroforestry	Gaussian

Grain weight	Farming system, weed cover, slug abundance. Separate models to test interaction between farming system and weed cover or slug abundance.	Site, year	Slug data filtered to only include pre-harvest records.	Gaussian
Apple seed counts	Year (as factor)	Site, OLRE	Orchards, separate model for each variety	Binomial
Apple seed counts	Farming system	Site, OLRE	Separate model for each variety	Binomial
Apple seed counts	Farming system, pesticide use (binary)	Site, OLRE	Separate model for each variety	Binomial
Equivalent annual value (EAV)	Farming system	-	-	Gaussian

A previous study found higher slug abundance and non-crop plant cover in agroforestry crop alleys compared with arable fields (Staton et al., 2021), using data collected from the same sample locations as the yield data in this study. Therefore, to investigate possible effects on yield, we tested associations between these two taxa with arable yield using mixed models (Table 1).

2.2 Apple pollination and yield (Question 2)

We sampled apple fruits from four UK agroforestry sites in August and September 2020 (Supplementary Material 1). At each site, between 40 and 100 apples were sampled to record maximum width and number of seeds. The number of fruits on each sampled tree was also recorded, except at the Norfolk site where the apples had already been harvested. We sampled two varieties: Bramley (a large culinary apple) from all four sites, and Braeburn (desert apples) from two sites (Supplementary Material 1). An equal number of Bramley and Braeburn were sampled at the latter two sites.

We estimated apple yield at each site based on the number of apples per tree and predicted apple weight, derived from the relationship between width and weight for both varieties in

Garratt et al. (2016b) (Supplementary Material 2). Predicted yields were compared to expected yields in the Organic Farm Management Handbook (Lampkin et al., 2017), because none of the apples in the agroforestry sites were treated with pesticides.

Seed counts per apple are a proxy for pollination service (Garratt et al., 2016a; Webber et al., 2020). Therefore, to compare pollination service, the seed set per apple from the agroforestry sites was compared to previously published orchard data in Garratt et al. (2016b). To compare this orchard dataset to 2020 conditions, we sourced 30 each of non-organic and organic Bramley, 40 non-organic Braeburn and 40 organic Braeburn apples from a wholesaler. These originated from orchards in Kent, UK, however no UK source was available for organic Braeburn, so this was sourced from Lower Saxony, Germany, which is climatically very similar to Kent. Maximum width and number of seeds were measured in these fruits.

The effect of year on seed count in orchard apples was tested using binomial GLMMs for each variety (Table 1). Year had no significant effect (Supplementary Material 3); therefore, 2016 and 2020 data were combined to test the effect of farming system (agroforestry versus orchard systems) on seed counts for each variety (Table 1). We also ran a separate model with pesticide use (organic/no-spray or conventional) as an additional fixed effect, although only one organic orchard site was available for each variety.

The value of pollination was estimated using formulae adapted from Garratt et al. (2014) (Supplementary Material 2), which compares pollination value between two treatments (in this case agroforestry versus orchard systems) based on differences in fruit set and weight. To control for confounding factors which could affect apple fruit set, weight and width, such as soil type, climate and management, only seed count data was used as empirical data input. Apple width, weight and fruit set were estimated using their relationships with seed count, based on the data in Garratt et al. (2016b) for each variety.

2.3 Carbon emissions and sequestration (Question 3)

To predict carbon dioxide emissions and sequestration, we primarily used the Farm Carbon Calculator (Farm Carbon Toolkit, 2020), which is a web-based carbon calculator, underpinned by peer-reviewed evidence, designed to assess emissions and sequestration on UK farms. We focussed on two factors: emissions from crop residues and sequestration from fruit trees. We took a conservative approach by not incorporating other factors such as machinery movements and inputs, because although these are likely to be reduced in the agroforestry system, there is uncertainty depending on management of the tree rows. Soil carbon stocks vary little between agroforestry and arable systems, according to recent modelling, so were not included here (Giannitsopoulos et al., 2020).

Reduction in emissions from crop residues depends on crop type and yield, so was modelled separately for each of three productivity levels (low, average and high, described further in Section 2.4.1), management system (conventional or organic) and crop type. Sequestration from fruit trees was based on the area they occupy (9.2%) in the modelled agroforestry system described at Section 2.4. The amount of carbon dioxide sequestered by apple trees, including below-ground sequestration, was assumed to be 3.3 or 5.0 t CO_2e/ha/year (Farm Carbon Toolkit, 2020; Page, 2011).

For each productivity scenario, we calculated the net difference in greenhouse gas emissions/sequestration, i.e. emissions in arable minus agroforestry systems, plus sequestration in the agroforestry system. Two scenarios for greenhouse gas (CO_2e) values were evaluated: (i) traded EU allowances, which reflect current and projected trading prices, and (ii) non-traded shadow price of carbon. The latter incorporates discounted future social costs of greenhouse gas emissions and can be interpreted as the government's willingness to pay for reductions in carbon emissions. Carbon prices were sourced from the UK's Green Book Supplementary Guidance (Department for Business, Energy & Industrial Strategy, 2019) and covered the period 2020 to 2039 to reflect predicted increases in carbon value over the next 20 years.

2.4 Gross Mixed Income (Question 4)

Financial cash-flow was quantified as gross mixed income (GMI), because this represents the most relevant outcome for small family businesses by representing joint income from their unpaid labour and capital investments, unlike profit which deducts all labour costs and is more relevant to corporations. The most established field site from which we collected empirical arable and apple data was used as a model system to investigate farm income (i.e. GMI) and the contribution of marketable ecosystem services, relative to an equivalent arable system. This site was Whitehall Farm, Cambridgeshire, UK (described in Newman et al. (2018)), where an agroforestry system was planted across approximately half of the farm (52 ha) in 2009, with the remainder retained as monoculture arable land. The modelled agroforestry system and arable controls were based on a theoretical 16 ha field (Supplementary Material 4), which is the average field size in Cambridgeshire, where over 80% of farmed land is arable (Robinson and Sutherland, 2002). We analysed economic performance over a 20 year period, because this is the typical duration of dessert apple trees (Redman, 2017).

To compare the financial performance of the agroforestry system compared with arable controls, we used the xlwings library in Python version 3.7.4 (Python Software Foundation, 2019) to manipulate inputs into the Excel-based Farm-SAFE economic model (Graves et al., 2011, 2007). Model outputs were similarly extracted with Python and plotted using the ‘ggplot2’ package in R version 3.5.2 (R Core Team, 2018; Wickham, 2016). The current value of future GMI was calculated as net present value (NPV, Equation 1), by reducing costs and benefits that occur in future years (Equation 2) by an annual discount rate, which was set at 3.5% (HM Treasury, 2018).

$$(1)\; NPV = \sum_{y=1}^{n} \left(\frac{GMI_y}{(1+r)^y} \right) - i$$

Where GMI = annual gross mixed income (Equation 2), i = capital investment costs based on scaled costs of orchard establishment (see Supplementary Material 6), n = total number of years (20, which is the typical duration of dessert apples (Redman, 2017)), r = discount rate (3.5%), and y = year after present (year 0).

$$(2)\ GMI = (yield \times price) + subsidies - variable\ costs - fixed\ costs$$

In Equation 2, yield and price represent both the apple and arable components of the system (explained in Sections 2.4.1 and 2.4.2). Apple yields were reduced in the first five years to account for establishment. Subsidies comprised Basic Payment Scheme plus greening, plus Countryside Stewardship organic payments for organic systems, and were equivalent for the agroforestry and arable systems (except for the case study, explained at Section 2.4.2). Variable costs included seed, fertiliser, sprays, and casual labour, plus annual pruning and harvesting of apple trees and removal of apple trees in year 20. Fixed costs included paid and casual labour, machinery, overheads, and rent. Further information on these parameters is provided in Supplementary Material 6.

We also calculated equivalent annual value (EAV, Equation 3), which represents NPV in annual terms (parameters are defined in Equation 1):

$$(3)\ EAV = \frac{NPV \times r}{1 - (1 + r)^{-n}}$$

All analyses used Euro currency for consistency with the Farm-SAFE model and previous associated publications, using an exchange rate of £1 = €1.18 based on the Bank of England’s spot exchange rate for the end of 2019 (Bank of England, 2020). Outputs are converted to pound sterling in Supplementary Material 5.

2.4.1 Theoretical GMI

We tested the theoretical GMI of the agroforestry versus arable systems using farm management handbooks, which provide cost, yield and price figures for low, average and high levels of production, reflecting farm-dependent factors such as soils, climate and farmer expertise (Lampkin et al., 2017; Redman, 2017). As the productivity level of combinable crops is not necessarily related to the apple crop, we modelled each combination of productivity level, for each management system (conventional versus organic). Therefore, 18 productivity scenarios were modelled (3 combinable crop yield levels x 3 apple yield levels x 2 management systems). In each scenario, the financial performance (NPV and EAV) of the agroforestry system was compared with the equivalent arable system.

Apple harvest costs (e.g. harvesting and packing, see Supplementary Material 6) were calculated per tonne of harvested apples. Otherwise, all parameters other than yield remained constant among productivity levels (Supplementary Material 6). The modelled conventional system was based on rotation of two years of winter wheat followed by a third year of oilseed rape (OSR). This is a widely used crop rotation in Europe, for example, OSR covered 380,000 hectares in the UK in 2020 (Defra, 2020), suggesting that this rotation occupies approximately 1 million hectares in the UK (assuming OSR recurs every three years). The modelled organic system comprised a six-year rotation of red clover, winter wheat, winter oats, spring beans, winter triticale, and spring barley, which has been recommended as a balanced rotation in the UK (HGCA, 2008). In all cases, the crops grown in comparable agroforestry and arable systems were the same, so that only the presence of agroforestry tree rows and the area occupied by combinable crops differed between the two systems.

2.4.2 Case study

Annual records of apple and combinable crop yields in the agroforestry and arable fields, collected by the farm manager at the Whitehall Farm site, were used to empirically test the GMI of the agroforestry versus arable systems. Because different fields within the farm are at different stages of rotation, we ran 1000 Monte Carlo simulations, with the crop rotation in each simulation randomised based on the proportion of crops in the actual rotation (Supplementary Material 7). The same crop type was applied to agroforestry and arable fields in each year. For each year, in each simulation, apple and combinable crop yields were randomly sampled from a normal distribution based on the mean and standard deviation of the empirical yield data. Equal arable yields were applied to each farming system, to reflect the comparable yields between farming systems at this site. Initial establishment costs were 1357 €/ha, based on actual data from Whitehall Farm. Fertiliser and apple protection (pesticide) costs were not included to reflect farm practices. A countryside stewardship AB8 grant (€636.02 per ha of trees) was included for the tree row flowering understorey, and establishment costs included. Otherwise, model parameters were applied according to the organic system at Supplementary Material 6. The effect of farming system on GMI (represented by EAV) was tested using a linear model (Table 1).

2.4.3 Sensitivity analysis

To investigate the sensitivity of GMI in the agroforestry system, the above case study analysis was run under the following scenarios (1000 simulations for each scenario): (i) low arable yields, reduced by 11.4% in the agroforestry system (based on barley/wheat yields in Section 3.1); (ii) low apple yields, comprising the lower estimate of observed agroforestry yields (4 t/ha, from the Whitehall Farm case study); (iii) high apple yields, comprising the upper estimate of observed agroforestry yields (14.84 t/ha, from Section 3.2); (iv) low apple prices, based on 100% processing (£0.2/€0.24 per kg (Lampkin et al., 2017)), to test a wholesale juicing market scenario rather than eating/cooking apples; and (v) the lower and upper estimates of carbon payments for the agroforestry system (based on Section 3.3).

3 Results

3.1 Cereal yields and associations with pests (Question 1)

Grain weight of barley or wheat was 11.4% lower in agroforestry than arable fields, which was statistically significant (t=-2.440, p-value=0.016), but grain weight of organic oats did not significantly differ between agroforestry and arable fields (t=-0.087, p-value=0.931). However, crop type was confounded with year, site and organic management, therefore differences in effects between crop types should be treated with caution. Yield of the pooled crop data was 17.2% higher at the centre of the alleys than at 0.5 m from tree rows, but this was not significant (t=1.796, p=0.077).

Cereal yield was significantly negatively associated with weed cover (t=-3.045, p-value=0.003), but was not significantly associated with slug abundance (t=-1.798, p-value=0.076). There was no significant interaction between farming system and either weed cover or slug abundance (Supplementary Material 3).

3.2 Apple pollination and yield (Question 2)

Estimated yields of agroforestry-grown apples ranged from 5.677 to 14.835 tonnes per ha of apples (Table 2). These values are comparable to expected yields from young organic orchards which typically yield 3 t/ha for years 1-5 and 16 t/ha for years 6-11 (Lampkin et al., 2017). Approximately 70% of Braeburn were of sufficient width for Grade 1 or 2 (Table 2), comparing closely with expectations for organic orchards (Lampkin et al., 2017).

Table 2. Estimated apple yields (per hectare of apples) at agroforestry sites, calculated based on the number of apples per tree and apple width. Grade 1/2 is based on maximum width of at least 60 mm. Apples per tree and yield could not be obtained from the Norfolk site because the apples were harvested prior to sampling.

Site	**Variety**	**Year of trees**	**Percentage grade 1/2**	**Mean apples per tree**	**Mean estimated weight per apple (g)**	**Estimated yield (t/ha, all grades)**
Nottinghamshire	Braeburn	7	68.7	48.7	104.74	5.677
Nottinghamshire	Bramley	7	100	69.8	191.19	14.835
Oxfordshire	Bramley	6	100	27.6	219.64	6.735
Cambridgeshire	Bramley	11	99	40.8	205.54	9.325
Norfolk	Braeburn	4	70	-	108.80	-
Norfolk	Bramley	4	99	-	184.46	-

Seed set in Bramley apple was significantly higher in four agroforestry sites than five orchard sites (mean 4.05 in agroforestry vs. 2.61 in orchards, z=2.108, p-value=0.035), indicating a higher level of pollination in the agroforestry system. This was however not significant when pesticide application on apples was included as a binary fixed effect (z=-1.110, p-value=0.267), although only one organic orchard site and no agroforestry sites with apple pesticide use were available. Seed set for Braeburn was not significantly different between two agroforestry and four orchard sites (z=-0.286, p-value=0.775), providing no evidence for a difference in pollination service. The value of pollination service in agroforestry-grown apples, relative to orchards, depended on variety and organic management, ranging from 104.08 €/ha compared with conventional Bramley orchards to -28.99 €/ha compared with organic Braeburn (Table 3).

Table 3. Value of pollination (€/ha/year of agroforestry) in no-spray agroforestry-grown apples, compared with orchards, using seed counts to predict apple weight, grading and fruit set. Positive values represent higher pollination value in agroforestry than orchard systems.

Apple production level	**Value of apple pollination in agroforestry compared with:**			
	Conventional		Organic	
	Bramley orchard	Braeburn orchard†	Bramley orchard*†	Braeburn orchard*†
Low	45.51	30.95	-1.81	-2.23
Average	74.80	50.86	-14.47	-17.84
High	104.08	70.78	-23.52	-28.99

* Only one site was available

† difference in seed counts between agroforestry and orchard systems was not significant

3.3 Added value from carbon sequestration / reduced emissions (Question 3)

The net reduction in carbon dioxide emissions in agroforestry compared with equivalent arable systems ranged from 312.9 to 552.4 kg CO_2e/ha/year (Table 4). The main contributor to this reduction, and determinant of variation therein, was carbon sequestration by apple trees. Using predicted market prices of carbon over the next 20 years, the equivalent annual value (EAV) of net carbon emission reductions in the agroforestry compared with arable systems ranged from 44.96 to 49.57 €/ha for the lower estimate of fruit tree sequestration, to 65.54 to 70.15 €/ha for the upper sequestration estimate (Table 5). Using non-market shadow price of carbon, these figures increased to 53.71 to 59.12 €/ha, and 78.26 to 83.66 €/ha (Table 5), for lower and upper sequestration estimates respectively.

Table 4. Modelled greenhouse gas (GHG) emission reductions and sequestration in the agroforestry versus equivalent arable systems. Ranges are given for reduction emissions as these depend on the crop stage of the rotation, and the range for fruit tree sequestration represents data from different studies.

System	**Production level**	**Reduction in emissions from crop residues (kg CO_2e/ha/year)**	**Sequestration from fruit trees (kg CO_2e/ha/ year)**	**Net change in GHG (kg CO_2e/ha/year)**
Conventional	Low	39.2 to 59.4	303.4 to 460.0	342.8 to 519.4
	Average	45.8 to 70.3		349.4 to 530.3
	High	52.3 to 81.9		355.9 to 541.9
Organic	Low	9.3 to 92.4		312.9 to 552.4
	Average	9.9 to 92.4		313.5 to 552.4
	High	1.2 to 92.4		315.3 to 552.4

3.4 Gross Mixed Income of the agroforestry system (Question 4)

3.4.1 Theoretical Gross Mixed Income

Modelling predicted that the agroforestry system was initially at negative cash-flow, arising from establishment costs and the time-lag before apples became productive. By the end of the 20-year simulation however, gross mixed income (GMI), represented by net present value (NPV) and equivalent annual value (EAV), in agroforestry was higher than for the equivalent arable systems in 15 of the 18 modelled scenarios (Fig. 1, Table 5). Of these 15, NPV in agroforestry exceeded the equivalent arable scenario after seven to 14 years (Table 5). The three agroforestry scenarios with lower GMI than arable systems were all organic systems with low apple productivity. In these scenarios, GMI (expressed as EAV) of the agroforestry system remained lower than for the equivalent arable system even without establishment costs.

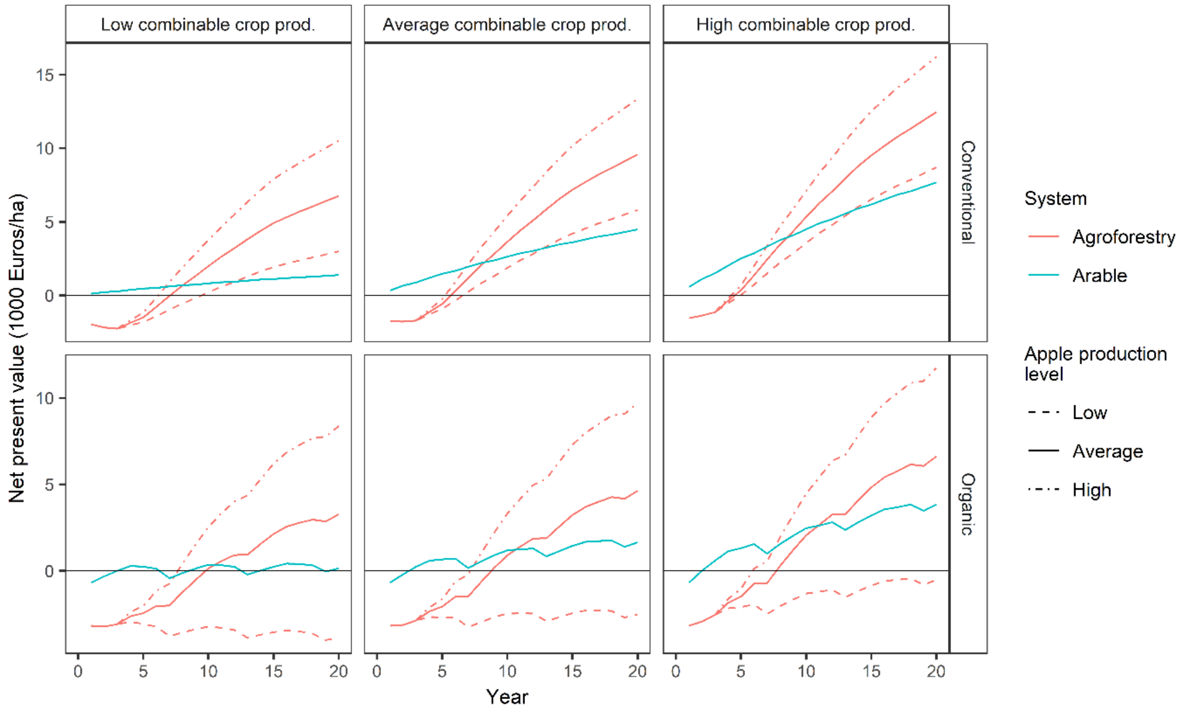

Figure 1. Modelled cumulative gross mixed income (expressed as net present value) of agroforestry versus arable systems over a 20-year system lifespan. Each column represents a combinable crop productivity level, whilst the rows represent conventional or organic management.

Table 5. Economic performance of agroforestry (AF) compared with equivalent arable systems, under 18 different scenarios of management regime, arable crop productivity level (PL) and apple productivity level (as defined by farm management handbooks). Cumulative gross mixed income is represented by net present value (NPV), whilst equivalent annual value (EAV) is the equivalent annual value for a 20-year system lifespan. All financial values (NPV/EAV) are expressed as €/ha.

Scenario			**Years for AF NPV to exceed arable NPV**	**Arable EAV**	**AF EAV with establishment costs**	**AF EAV without establishment costs**	**Carbon EAV (market price)**	**Carbon EAV (shadow price)**
Inputs	**Arable PL**	**Apple PL**						
Conventional	Low	Low	12	97.01	210.35	352.20	46.97 – 67.56	56.02 – 80.57
	Low	Average	9	97.01	475.23	617.07		

	Low	High	7	97.01	740.10	881.95		
	Average	Low	13	315.43	408.68	550.52	48.24 – 68.82	57.54 – 82.08
	Average	Average	9	315.43	673.55	815.40		
	Average	High	7	315.43	938.43	1080.27		
	High	Low	14	539.84	612.45	754.29	49.57 – 70.15	59.12 – 83.66
	High	Average	9	539.84	877.32	1019.17		
	High	High	7	539.84	1142.19	1284.04		
Organic	Low	Low	Infinite	10.41	-272.74	-95.85	44.96 – 65.54	53.71 – 78.26
	Low	Average	11	10.41	230.09	406.99		
	Low	High	8	10.41	589.26	766.15		
	Average	Low	Infinite	115.92	-176.94	-0.04	45.41 – 65.99	54.24 – 78.79
	Average	Average	11	115.92	325.90	502.79		
	Average	High	8	115.92	685.06	861.96		
	High	Low	Infinite	270.47	-36.61	140.29	45.50 – 66.58	54.93 – 79.47
	High	Average	11	270.47	466.22	643.11		
	High	High	8	270.47	825.39	1002.28		

3.4.2 Modelled GMI based on a case study agroforestry system

Cereal yields at the case study farm were similar between agroforestry and arable fields, and were similar to or higher than those stated in the Organic Farm Management Handbook for a high productivity level organic farm, while apple yields were between low and medium productivity levels (Lampkin et al., 2017). According to 1000 simulations using random samples taken from the empirical data, the EAV of the agroforestry simulations over the 20-year system lifecycle was 10.25 €/ha (8.69 £/ha) higher than the equivalent arable simulations. Cumulative GMI (expressed as NPV) of the agroforestry system was higher than the arable system within the 20-year lifecycle in 75.7% of cases. In those cases, the agroforestry system was initially at negative cash-flow but NPV exceeded the equivalent arable system after a mean of 17.79 years. This is consistent with the theoretical expectation for an organic farm with high arable productivity and low to average apple productivity (Table 5).

3.4.3 Sensitivity analysis

Sensitivity analysis of the above case-study simulation identified that apple yield and price were the major factors determining GMI of the agroforestry system (Fig. 2). For example, simulations based on the upper estimate of apple yield (14.49 t/ha) increased EAV of the agroforestry system by 61% compared with the baseline scenario where mean apple yield was 4.81 t/ha. Simulations assuming wholesale processing prices for all apples (£0.2/€0.24 per kg) reduced EAV by 36% compared with the baseline assumption of 70% Grade 1 or 2 wholesale apples.

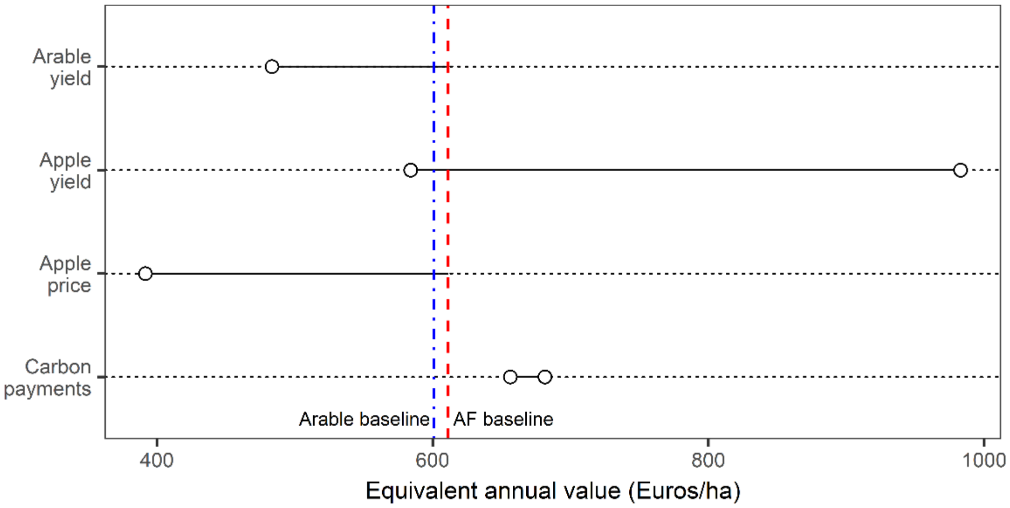

Figure 2. Sensitivity analysis to compare alternative scenarios for the agroforestry system. The arable and agroforestry (AF) baseline scenarios are mean equivalent annual values (EAV) from the case study simulation (Section 3.4.2). The points represent mean EAV of agroforestry under the following scenarios, with inputs manipulated in isolation: the arable yield scenario assumes 11.4% reduction in arable yield in the agroforestry system (from Section 3.1), the apple yield scenarios represent the minimum yield recorded from the case study farm (4 t/ha, excludes establishment years) and the maximum yield from an agroforestry system (Section 3.2), the low apple price scenario assumes a processing price of 0.24 €/kg for all apples (compared with 70% Class 1/2 at 1.06 €/kg for the baseline scenario), and the carbon scenarios represent grant payments for carbon sequestration (Section 3.3).

4 Discussion

In this study we (i) compared empirical arable and apple yields between agroforestry and monoculture (arable/orchard) systems, (ii) evaluated the costs and benefits of weed/pest pressure, apple pollination, and carbon sequestration in terms of productivity and/or gross mixed income (GMI), and (iii) modelled GMI of the agroforestry versus arable systems. We found 11% lower wheat/barley yields in the agroforestry than arable system, but no significant effect for oat yield, while there were significant negative associations between yield and weed cover. Apple yields in the agroforestry system were highly variable among sites and varieties, but were consistent with expected yields in comparable orchards. Apple pollination level, as indicated by seed set, was significantly higher in agroforestry-grown Bramley apples than conventional orchards, but there was no significant difference after accounting for pesticide use, or for Braeburn apples. Cumulative GMI of the agroforestry system was predicted to be higher than that of an equivalent arable system within a 20-year lifespan, except in low production, organic systems. Financial modelling of a case study system, using empirical data, was consistent with theoretical predictions. A sensitivity analysis demonstrated that apple yield and price were the major determinants of GMI of the agroforestry system, and were capable of more than compensating for an 11% reduction in arable yield. Carbon sequestration and reductions in emissions added further value to the agroforestry system.

4.1 Cereal productivity

Our finding of lower wheat/barley yields in the agroforestry compared with arable systems is consistent with short-term yield reductions in other diversified farming systems (reviewed in Rosa-Schleich et al., 2019). The 11% yield reduction compares favourably to the 10-26% reductions for barley and 11-15% reductions for wheat in a timber agroforestry system with 12 m wide alleys (García de Jalón et al., 2017; Giannitsopoulos et al., 2020). Furthermore, in that timber system, arable cropping was predicted to be unprofitable after 5 to 13 years depending on alley width (Burgess et al., 2003), whereas continuous arable cropping appears to be financially viable in the apple-arable agroforestry system, albeit longer-term yield monitoring is needed. Our yield effects however compare less favourably to the reported 16% increase in wheat yield in a short-rotation coppice system with 48 m wide alleys (Kanzler et al., 2019), while another study found similar yields between short-rotation coppice systems with 48 and 96 m wide alleys, and arable control fields (Swieter et al., 2019). Although the effects of farming system on yield of different crop types was confounded with site and should be interpreted with caution, we found comparable oat yields between the agroforestry and arable systems, possibly because oats are more competitive with weeds and resistant to slug damage than wheat or barley (Douglas and Tooker, 2012; Seavers and Wright, 1999).

We found a negative relationship between cereal yields and proximity to tree rows, although the results were not statistically significant (p-value=0.77). Nevertheless, alley width is likely to be an important factor when comparing yields between agroforestry and arable systems (Burgess et al., 2003). For example, according to a meta-regression, tree rows and hedgerows reduce yields of adjacent crops, relative to arable controls, up to a distance into the crop alley of 1.64 times the tree height (Van Vooren et al., 2016), but have positive or negligible effects thereafter. This translates to approximately half of the crop alley in an apple-arable agroforestry system with 24 m wide alleys and MM106 rootstocks, where the trees reach approximately 4 m height, which are typical choices for modern agroforestry systems.

Competition between trees and arable crops for resources such as water, light and nutrients has been cited as the major cause of arable yield reductions in agroforestry systems (Jose et al., 2004), although cultivar selection programs have potential to mitigate this (Arenas-Corraliza et al., 2021). Our finding of negative associations between weed cover and yield suggests that weed competition could also be a factor in organic agroforestry systems, although we cannot demonstrate any causal relationship. Previous studies have shown that weed cover in agroforestry versus arable systems varies among sites, possibly depending on the response traits of the dominant weed species (Boinot et al., 2019; Staton et al., 2021), suggesting that this potential cause of yield reduction may only apply to sites with problematic creeping, perennial weeds. Similarly, slug abundance has previously been linked to pea crop damage in agroforestry crop alleys (Griffiths et al., 1998). We found no significant evidence for this based on spring counts, although autumn and winter slug abundance may be of more relevance for winter-sown crops.

Despite the short-term negative effects on wheat/barley yield, yield stability is typically higher in diversified farming systems compared with non-diversified systems (Rosa-Schleich et al., 2019), including intercropping of annual crops (Raseduzzaman and Jensen, 2017), while proximity to semi-natural habitats improves yield resistance to extreme weather events (Redhead et al. 2020). Agroforestry systems could improve yield stability and climate resilience by moderating the impacts of extreme weather events, such as drought and high winds (Arenas-Corraliza et al., 2018; Kanzler et al., 2019), and in the longer-term, protection from soil erosion (Tsonkova et al., 2012; Varah et al., 2013). Natural enemy activity has also been postulated as a probable mechanism for higher yield stability with proximity to semi-natural habitat (Redhead et al., 2020), and agroforestry systems increase the functional trait diversity of natural enemies compared with arable monocultures (Staton et al., 2021).

4.2 Apple productivity and pollination

We found that apple yields in the agroforestry system strongly varied among sites, even for the same variety. Possible explanations for this variation are differences in site conditions such as soil type, management (e.g. pruning), alternate bearing (natural yield fluctuations between years), and tree age, which varied from 6 to 11 years, the youngest of which had only just entered full production. Productivity data from this novel agroforestry system are scarce, although Smith et al. (2016) also found substantial variation in apple yields; depending on variety and year, yields varied from 0.25 to 15.18 t/ha (of apple trees) for the 5-6 year old Cambridgeshire system also used in our study, and 15.7 to 19.25 t/ha for a 18-19 year old system which used MM111 rootstocks. At the Cambridgeshire site, Bramley yields of 0.35 and 3.71 t/ha were reported in 2014 and 2015 respectively, compared to our finding of 9.33 t/ha in 2020. The existing data tentatively suggests that fruit trees in agroforestry settings could take longer than expected to enter full production, possibly because the understorey vegetation competes for resources (Granatstein and Sanchez, 2009) and because of the more exposed conditions.

Pollination levels in Bramley, represented by seed set, were significantly higher in the agroforestry system than in conventional orchards, but preliminary findings from one organic orchard suggest similar levels to the agroforestry sites. Furthermore, we found no significant difference between agroforestry and orchard systems for Braeburn seedset, suggesting that the comparison between agroforestry and orchard systems is complex and moderated by other factors such as variety and pest management. Nevertheless, our findings suggest that the more exposed conditions and lower densities of apples trees in agroforestry compared with orchard systems does not substantially reduce seed set.

4.3 Carbon sequestration

We estimated a reduction in greenhouse gas emissions in the agroforestry compared with arable systems of 312.9 to 552.4 kg CO_2e/ha/year, the majority of this (83 to 97%) being attributable to sequestration by trees. This is at the lower end of the predicted range of 366 kg to 11 t CO_2e/ha/year for tree sequestration over a 60-year simulation of European agroforestry systems (Palma et al., 2007a). While sequestration will inevitably be lower than fast-growing timber agroforestry systems (e.g. Giannitsopoulos et al., 2020), our results suggest that the apple-arable agroforestry system can make a meaningful contribution to climate change mitigation in agriculture, which we value at between 44.96 and 70.15 €/ha per year (equivalent to net present value (NPV) of 639 to 997 €/ha) using predicted market carbon prices, or 53.71 and 83.66 €/ha per year (NPV of 763 to 1189 €/ha) for non-market shadow price. Given the reported establishment costs of 1357 €/ha of the agroforestry system (Newman et al., 2018), an upfront carbon payment would cover 47% to 73% of these costs using market prices, or 56% to 88% using shadow prices.

4.4 Farm Income

Cumulative gross mixed income (GMI) of the agroforestry system was consistently predicted to be higher than of the equivalent arable systems within a 20-year system lifespan, with the exception of organic systems with low apple productivity. Apple productivity and price were the most important factors determining GMI of the agroforestry system, and were capable of substantially outweighing an 11% reduction in cereal yield. For example, by assuming apple yields were consistently at the maximum recorded in the study, equivalent annual value (EAV) of GMI increased by €349 compared with the baseline agroforestry scenario, while the difference between 70% Class 1 or 2 and 100% processing wholesale prices represented €233 EAV. These compare to a loss of €147 EAV resulting from an 11.4 % reduction in arable yields in the agroforestry system. These figures demonstrate the importance of proper management and protection (i.e. staking and shelterbelts) of apple trees, availability of sufficient labour, and identification of markets, particularly given that this agroforestry system is typically implemented by arable farmers without prior experience of apple production. In addition, further research is needed to identify which apple varieties are best suited to agroforestry conditions (Smith et al., 2016).

The expected time taken for cumulative GMI (expressed as NPV) of the agroforestry system to exceed arable was 7 to 14 years in the theoretical systems (for the 15 of 18 cases where the GMI of the agroforestry system exceeded that of the equivalent arable system), depending on organic management and productivity level. This increased to 18 years in the case study system, because of relatively low apple yields and high arable yields. Nevertheless, this still compares favourably to timber agroforestry systems, where a return on investment is not expected until at least 20 years (Graves et al., 2007; Van Vooren et al., 2016), and is dependent on timber prices, grant payments and discount rates (Giannitsopoulos et al., 2020; e.g. Palma et al., 2007b; Toor et al., 2012).

The adoption of agroforestry systems is mainly constrained by management and labour complexity factors (García de Jalón et al., 2018). Although our results suggest that agroforestry can increase GMI relative to arable systems, in order to effectively promote agroforestry systems, farmers need to perceive that the benefits such as long-term GMI exceed the perceived drawbacks. A wider valuation of non-marketable ecosystem services could therefore help to promote these systems.

4.5 Other ecosystem services

Previous studies have demonstrated the potential for agroforestry systems to provide other ecosystem services. For example, the value of reduced soil erosion by water, and balances of nitrogen and phosphorous have been estimated at 5, 8 and 18 €/ha/yr respectively in a UK silvoarable system compared with an arable control (Giannitsopoulos et al., 2020). In that case study, the arable crop alleys were put to grass fallow after 14 years of the 30-year system lifespan, therefore the value of these services in our study system is likely to be less, assuming continuous arable cropping. Another important ecosystem service in some regions is soil protection from wind, which to our knowledge has not yet been assessed in agroforestry systems, and would be strongly spatially dependent. A holistic monetary quantification of the ecosystem services provided by agroforestry, for example extended accounting systems such as the Agroforestry Accounting System, would help to inform the design of public policies to promote the adoption of these systems (Campos et al., 2020; Giannitsopoulos et al., 2020).

4.6 Constraints and research needs

Our results are based on arable and apple yield data collected over two years from five agroforestry sites, the most established being 11 years. As such they would benefit from further, long-term replicated studies and validation from other sites and from more established systems. Long-term yield data is important to investigate biodiversity benefits, yield stability and implications for food security. In addition, our assessment of pest and weed impacts on crop yields are based on associations, rather than demonstrating causal relationships. Further research is needed to quantify the impacts of changes in pest abundance on chemical control costs (Johnson et al., 2020). Our comparison of apple pollination is constrained by confounding factors, particularly organic management, tree age and landscape context, and would benefit from further investigation to disentangle these factors.

Land equivalent ratios (LERs) are a common method for comparing productivity between agroforestry systems and equivalent monocultures. LER calculates the area of monoculture required to achieve the same level of productivity of one unit of polyculture, and was originally devised for intercropped annual crops (Mead and Willey, 1980). We did not calculate LER in this study because: (i) we did not have empirical or robust modelled yield data for the lifespan of the system, particularly for apples, (ii) we did not have comparable monoculture apple (orchard) yield data, (iii) as discussed by Newman et al. (2018), the method for LER calculations in previous studies of agroforestry systems is inconsistent, because studies variously use yield per area of the crop component or per area of agroforestry. This leads to problems in comparing LER calculations from previous studies. A synthesis of previous LER agroforestry studies using a standardised methodology would help overcome this problem, and the data we present in this study could potentially be used in any such future synthesis, notwithstanding the above constraints.

4.7 Conclusion and implications

There appear to be trade-offs from higher biodiversity in agroforestry systems; weed cover was negatively associated with arable yields, but Bramley apple seed set, which indicates pollination level, was higher in agroforestry than conventional orchard systems. Organic management was a complicating factor however, and requires further investigation. In addition, further research is needed to investigate yield stability in agroforestry systems arising from the higher functional diversity of natural enemies.

Apple yield and price were the major determinants of gross mixed income (GMI) of the agroforestry system, and were capable of compensating for an 11% wheat/barley yield reduction in the long-term. However, the time-lag for the GMI of the agroforestry system to exceed that of the equivalent arable system was substantial (at least 7 years), while labour and expertise requirements represent additional barriers. Hence, policy support in the form of establishment grants would help to promote these systems. This could be partially met by up-front payments for carbon sequestration.

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6 Supplementary Material

Supplementary Material 1. Descriptions and photographs of field sites.

Supplementary Material 2. Methods for predicting apple weight and pollination valuation.

Supplementary Material 3. Detailed model outputs.

Supplementary Material 4. Attributes of the theoretical modelled agroforestry system.

Supplementary Material 5. Results converted to pounds sterling.

Supplementary Material 6. Data sources.

Supplementary Material 7. Case study further information.

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